

Superdisks in Radio Galaxies: Jet–Wind Interactions

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ABSTRACT

Taking a clue from their sharp-edged (strip-like) morphology observed in several cases, a new mechanism is proposed for the formation of the emission gaps seen between the radio lobes of many powerful extragalactic double radio sources. Canonical understanding of the radio gaps invokes either blocking of the back-flowing lobe plasma by the denser interstellar medium (ISM) of the host galaxy, or “squeezing” of the radio bridge in the middle through buoyancy force exerted by either the ISM or the surrounding intra-cluster medium (ICM). These pictures encounter difficulties in explaining situations where the sharp-edged radio gaps associated with non-cluster radio galaxies have widths running into several tens (even hundreds) of kiloparsecs. More particularly, the required dense high-pressure ISM/ICM is likely to be lacking at least in the case of high-redshift radio galaxies. We propose here that radio emission gaps in at least such cases could arise from a dynamical interaction between the powerful thermal wind outflowing from the active galactic nucleus and the back-flowing synchrotron plasma in the two radio lobes, which occurs once the rapidly advancing jets have crossed out of the wind zone into the intergalactic medium. A simple analytical scheme is presented to explore the plausibility of the side-ways confinement of the thermal wind by the radio lobe pair, which would “freeze” pancake shaped conduits in the space, along which the hot, metal enriched wind from the AGN can escape (roughly orthogonal to the radio axis). Some other possible consequences of this scenario are pointed out.

Key words: galaxies: active – galaxies: jets – radio continuum: galaxies

1 INTRODUCTION

Over the past few decades, aperture-synthesis observations of radio galaxies have yielded, with increasing precision, maps of the synchrotron plasma deposited by the jet pair near their extremities (hot spots) as they advance through the ambient medium. Already from comparison of the early high-resolution observations made at centimetre and metre wavelengths (Jenkins & Scheuer 1976; Gopal-Krishna & Swarup 1977), it was strongly hinted that the pair of radio lobes arising from the backflow from the two hotspots are often separated by an emission gap which is probably real, and not merely a result of radiative losses. Such emission gaps, particularly the largest of them, will be the focus of the present study. According to one interpretation, the central gap in the “radio bridge” arises from blocking of the backflowing radio plasma by the denser interstellar medium

(ISM) of the parent elliptical galaxy (e.g., Leahy & Williams 1984; Alexander 1987; Wiita & Norman 1992). However, the general applicability of this mechanism was found to be at odds with the observation that in several powerful radio galaxies at moderate redshifts, the radio gaps have sharp, quasi-linear edges and some of these have widths approaching or even exceeding 100 kpc (Gopal-Krishna & Wiita 1996; Gopal-Krishna & Nath 1997; Gopal-Krishna & Wiita 2000, hereafter GKW00).

In these papers we argued that such emission gaps, or “superdisks”, can provide consistent explanations for some key correlations found among radio source properties, such as the Laing-Garrington effect (Garrington et al. 1988; Laing 1988; Garrington, Conway & Leahy 1991), the correlated radio-optical asymmetries (e.g., McCarthy, van Breugel & Kapahi 1991), the preference of multiple absorption dips to occur in the Ly- α profiles of high- z radio galaxies with overall sizes below ~ 35 kpc (van Ojik et al. 1997; Binette et al. 2006) and metrewave flux variability via “superluminal refractive scintillations” (Gopal-Krishna 1991; also, Campbell-Wilson & Hunstead 1994; Ferrara & Perna 2001). Another

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interesting property hinted by the GKW00 sample of superdisks was that the hot spots in the radio lobe pair are usually located more symmetrically about the superdisk's mid-plane than about the host galaxy, possibly signifying the galaxy's motion during the AGN phase (see Sect. 4).

In high redshift radio galaxies, the apparent asymmetry of diffuse Ly α emission, which is a sensitive tracer of dust, can be understood if the brighter Ly α emission is associated with the radio lobe on the near side of the nucleus and thus not obscured by any dust present in the superdisk (GKW00). Because the sharp-edged morphology would only be noticed when the radio jets are quite close to the plane of the sky, they are subject to a strong negative selection effect, and GKW00 argued that even though the observed cases of superdisk are few, the phenomenon may not be rare.

Initially we proposed that the superdisk is primarily made of the interstellar medium bound to the radio galaxy (RG) itself, perhaps originating from the gas belonging to gas-rich disk galaxies previously captured by the giant elliptical host of the powerful RG (e.g., Statler & McNamara 2002). We argued that the tidal stretching and heating of that gas during the capture was sufficient to produce very large fat pancakes (Gopal-Krishna & Nath 1997; GKW00). Since in some extreme cases (e.g., 0114–476; Saripalli, Subrahmanyan & Udaya Shankar 2002) the width of the superdisk was found to run into several hundred kiloparsecs, an alternative possibility was also put forward in GKW00, according to which at least some superdisks trace the gaseous filaments of the “cosmic web”. Earlier, noticing the straight, abrupt inner boundaries of the lobes in a radio galaxy (3C 227), Black et al. (1992) had inferred a “disc of central dense, cold gas with axis coincident with that of the source”. Very recently, Gergely & Biermann (2007) have proposed that superdisks can be carved out by the powerful wind produced due to a rapid jet precession during the impending merger of two supermassive black holes belonging to a pair of merging galaxies.

A popular explanation for the emission gaps, in general, invokes a squeezing or pinching of the (lighter) synchrotron plasma of the radio bridge in the middle, by the denser, higher pressure ISM, or circum-galactic medium, associated with the parent galaxy (e.g., Scheuer 1974; Croston et al. 2004b). While it is presently unclear how this process can account for the gaps with sharp, straight boundaries, the existence of such a medium is indeed supported by the detection of resolved X-ray emission from many massive ellipticals hosting double radio sources at small to medium redshifts (e.g. Hardcastle & Worrall 2000). This ISM is likely to be built up through a gradual accumulation of the gas lost by the stellar population over the Hubble time and heated to $\sim 10^6 - 10^7$ K due to mixing within the galaxy dominated by random motions (Brighenti & Mathews 1997 and references therein; O'Sullivan, Forbes & Ponman 2001).

On the other hand, massive ellipticals at high redshifts are expected to lack a significant amount of high-pressure ISM. Then the medium around even massive galaxies situated in groups and clusters will resemble peaks in the intergalactic medium (IGM) (and not the higher pressure intra-cluster medium which is typical of their lower redshift counterparts) due to an early stage of gas accretion from the cosmic web and its virialization. Based on sensitive optical/X-ray observations and cosmological simulations, clusters at

$z > 1.5$ are believed to be proto-clusters which would have grown into the present-day clusters by the process of virialization and merger with other clusters or galaxy groups (e.g., Miley et al. 2004; Ford et al. 2004; also, Rowley, Thomas & Kay 2004; Motl et al. 2004; Tormen, Moscardini & Yoshida 2004). Significant concomitant enrichment of the ICM is also expected via galactic winds and ram-pressure stripping of the galaxy population (e.g., Kapferer et al. 2007).

Our premise that distant radio galaxies have a circum-galactic medium at a significantly lower temperature/pressure than do nearer ones is supported by the deep *Chandra* observations which show that spectroscopically selected high redshift ($z \sim 1$) clusters and groups of galaxies are under-luminous, compared to their low redshift counterparts (Fang et al. 2006). A similar result is reported for medium redshift groups of galaxies (Spiegel, Paerels & Scharf 2007). The lower X-ray output probably indicates that these high- z systems have yet to accrete adequate hot gas and/or being dynamically younger systems, they are not yet virialized. It is thus expected that the (forming) clusters at high redshifts would be lacking a dense high-pressure medium found within nearby clusters and groups of galaxies. It may be noted that although X-ray emission extended on at least 100 kpc scales has been detected around the $z = 1.786$ quasar 3C294 and the $z = 2.48$ RG 4C 23.56 from deep *Chandra* observations, it is more likely to be inverse Compton boosted cosmic microwave background, as its energy density is much greater at such high redshifts (Fabian et al. 2003; Johnson et al. 2007; see also, Celotti & Fabian 2004). These considerations motivate us to explore in this paper an alternative mechanism that could be effective in the formation of emission gaps between the radio lobes in higher redshift radio galaxies.

Non-relativistic winds, with speeds often exceeding 10^3 km s $^{-1}$ and a mass outflow rates often greater than $1 M_{\odot}$ yr $^{-1}$ (e.g., Soker & Pizzolato 2005; Brighenti & Mathews 2006; Crenshaw & Kraemer 2007; Tremonti, Moustakas & Diamond-Stanic 2007) are now thought to be an integral part of the active galactic nucleus (AGN) phenomenon, and can be launched from accretion disks via several mechanisms (e.g., Narayan & Yi 1994; Königl & Kartje 1994; Blandford & Begelman 1999; Das et al. 2001). Evidence for such outflows comes from their absorption of the underlying continuum in the UV and/or X-rays (e.g., PDS 456, Reeves, O'Brien & Ward 2003; PG 1211+143, Pounds et al. 2003; NGC 1097, Storchi-Bergmann et al. 2003; see Crenshaw, Kraemer & George 2003 for a review). Such relatively slow winds and relativistic jets may coexist in many objects (e.g. Binney 2004; Gregg, Becker & de Vries 2006). As these non-relativistic winds, together with any existing relativistic jets, are believed to carry a mechanical luminosity far in excess of the synchrotron luminosity (e.g., Willott et al. 1999), they are capable of significantly influencing important phenomena such as cooling flows in clusters (e.g., Omma & Binney 2004; Soker & Pizzolato 2005; Brighenti & Mathews 2006), and even the structure formation in the universe (e.g., Rawlings 2003; Gregg et al. 2006). It is certainly possible that the jets contain significantly more mechanical energy than do the winds (Rawlings 2003), and that the mechanical power extracted from the central engine can sometimes greatly exceed its bolometric luminosity (Churazov et al. 2002, 2005; Peterson & Fabian 2006). An interesting question is: *what*

sort of interactions might occur between these two kinds of outflows of AGN power? Here we examine this issue and propose that at least some of the radio emission gaps, particularly in radio galaxies at higher redshifts, could well be manifestations of such an interaction.

Association of non-relativistic outflows with the accretion process has been discussed in many studies. An example is the “advection dominated inflow-outflow solution” (ADIOS) model (e.g., Blandford & Begelman 1999). In this model, most of the gravitational energy released during accretion onto a BH gets used up in driving a wind from the surface of the accretion disk. Thus, most of the gas falling on the outer edges of the disc is carried away by the wind roughly at the local Keplerian speed. In contrast, relativistic jets in RGs may be energized by the spin of the BH (e.g., Blandford & Znajek 1977; also, Wilson & Colbert 1995) and are almost certainly launched from the innermost portion of the central engine (e.g., Meier 2003). The ejection of relativistic jets probably marks a later phase in the accretion process (e.g., Rawlings 2003; Gregg et al. 2006). Another key difference between the two kinds of outflows is that the non-relativistic wind is likely to be much less collimated and, on the scale of 100 kpc, it almost certainly could be regarded as quasi-isotropic (e.g., Levine & Gnedin 2005). For the purpose of the exploratory calculations presented here we shall follow these last authors and adopt a spherical geometry for the non-relativistic wind outflow. We then proceed to analytically compute the interaction of the radio jets with an older phase of AGN activity which leads to winds that can blow up large “bubbles” of hot thermal gas around the elliptical galaxy hosting the AGN. Thus, in this picture, a central radio emission gap or even a superdisk in a high- z RG is created by the RG itself, but it is not predominantly comprised of the host galaxy’s interstellar medium (either captured or due to stellar winds). In Section 2 we discuss the basic idea and note some relevant observations. Section 3 presents a simple analytical framework for this two phase model of AGN activity. Some possible implications of this scenario are discussed in Section 4.

2 RADIO GALAXIES WITH CENTRAL EMISSION GAPS

Assume the formation of a powerful AGN begins with the launching of a thermal gas outflow from the nuclear region in the form of bubbles which coalesce into a single bubble (e.g. Di Matteo, Springel & Hernquist 2005; Gregg et al. 2006). As this bubble of hot thermal wind expands it approaches a roughly spherical shape; it also will eventually tend to reach pressure equilibrium with the IGM. At some later time, but typically before the bubble/IGM equilibrium is reached, the radio jets are launched from the same AGN in two opposite directions.

We reiterate that the situation will be significantly different for radio galaxies forming in situations where hot, X-ray emitting gas at significantly higher pressure is the norm, such as those within well developed clusters or groups of galaxies, or in massive ellipticals at low redshift. Under those circumstances much smaller bubbles of a few kpc radius will normally be inflated by the winds and/or radio jets (e.g. Dunn & Fabian 2006; Sternberg, Pizzolato & Soker 2007).

Although these bubbles may not lead to substantial density changes in the circumgalactic medium, they would give rise to patchiness in the X-ray emission. Examples of such patchiness can be found in the *Chandra* images of some nearby X-ray bright clusters, such as Perseus (Fabian et al. 2000), A262 (Clarke et al. 2007) and 2A0335+096 (Mazzotta, Edge & Markevitch 2003). These clusters provide examples where X-ray patchiness is widespread in the cluster core and much of it does not correlate with radio emission or jet axis; hence it could arise from bubbles of thermal plasma ejected from the AGN.

Initially, the radio jets will propagate within the region of the bubble (the wind zone). However, since the leading edges of the jets can advance much faster than the bubble’s expansion, the resulting hotspots would soon emerge out of the bubble. The relativistic plasma back-flowing from them would now begin to “impinge” on the bubble’s surface from outside. Although a majority of radio lobes seem to be roughly pressure matched with the ambient medium into which they are expanding (e.g., Hardcastle & Worrall 2000; Hardcastle et al. 2002; Croston et al. 2004a), over-pressured lobes also exist. For instance, such a situation has been found even for highly expanded radio lobes associated with giant radio galaxies (Kronberg et al. 2001). In the framework of our model, it is such radio sources that are more conducive to the formation of superdisks. Although the lobes can be significantly overpressured, the bubble is typically only marginally so, and hence the lobes can be expected to prevent the expansion of the wind bubble in their direction (i.e., along the radio axis). Taking into account the backflow within the lobes one can expect even compression of the wind bubble along the radio axis. Such a sustained squeezing from two opposite sides could transform the wind bubble into a fat disk. This would sometimes appear as a “chimney” when projected on the sky. This process of sideways compression or constriction by the lobe pair would deflect and accelerate the outflowing AGN wind roughly normal to the jet direction, through the putative fat disk. Note that in this picture, the boundaries of the radio gaps are identified as *lobe-wind interfaces*.

Unfortunately, radio maps of good enough quality to convincingly reveal a superdisk (SD) morphology are presently available only for relatively nearby RGs ($z < 0.6$), and for them there is a high probability of substantial amounts of circum-galactic hot gas being present that could confine the bubble and even the radio lobes. Obtaining good evidence for SDs from radio maps of galaxies at the higher redshifts for which external hot gas is less likely to be important is quite difficult. Such radio maps require a combination of high angular resolution, excellent sensitivity and high dynamic range, and this is particularly hard to achieve because of the $(1+z)^{-4}$ dimming of surface brightness. In addition, these observations would preferably be made at lower frequencies where morphologies of the lobes are best discerned. Nonetheless, a small number of somewhat higher redshift candidate SDs can be located in the literature, e.g.: 0838+133 ($z = 0.684$; Sambruna et al. 2004); 3C 265 ($z = 0.811$; Bondi et al. 2004); 1040+123 ($z = 1.029$; Sambruna et al. 2004).

Additional evidence for SDs in high- z RGs comes, at present, from optical detections of the strong Ly α emission associated with the RGs. This often very extended

Ly α emission traces any dusty screen of gas because resonant scattering greatly enhances the absorption of these photons by dust (e.g., GKW00). All the radio-loud objects with two-dimensional Ly α images showing substantial asymmetries of which we are aware are, in order of increasing distance: 3C 294 ($z = 1.82$; McCarthy et al. 1990); 3C 326.1 ($z = 1.82$; McCarthy et al. 1987); 1138–262 ($z = 2.16$; Pentericci et al. 1997); 0200+015 ($z = 2.23$; Jarvis et al. 2003) 0852+124; ($z = 2.47$; Gopal-Krishna et al. 1995); B3 J2330+3927 ($z = 3.09$; Pérez-Torres et al. 2006); MRC 0316–257 ($z = 3.13$; Venemans et al. 2005); 6C 1232+39 ($z = 3.22$; Eales et al. 1993); 1243+036 ($z = 3.57$; van Oijk et al. 1996); 4C 41.17 ($z = 3.80$; Chambers, Miley & van Breugel 1990); and 8C 1435+635 ($z = 4.26$; Spinrad, Dey & Graham 1995). For six of the seven RGs from this list for which the orientation of the radio lobes can be determined, the Ly α asymmetry is in the sense that stronger emission is seen from the side of the approaching lobe. Thus, the most likely explanation is that the Ly α photons coming from the farther side of the active nucleus are being obscured by a large gas disk around the parent galaxy (GKW00).

3 JET–BUBBLE INTERACTIONS

3.1 Wind Blown Bubbles

Levine & Gnedin (2005) have recently modelled expansion of hot thermal wind outflowing from an AGN. In this scenario they combine cosmological simulations with an AGN luminosity function and place the AGN at local IGM density peaks. They find that large portions of the IGM can be filled with such outflows unless kinetic luminosities are $< 10\%$ of the bolometric luminosities. This remarkable conclusion is similar to that reached by Furlanetto & Loeb (2001) for similar spherical outflows and by Gopal-Krishna & Wiita (2001) and Kronberg et al. (2001) for outflows in the form of relativistic jets (cf. Barai & Wiita 2007). Therefore, the impact of AGNs on the formation of structure in the universe may be quite significant, by triggering/accelerating global star formation in a multiphase intergalactic medium (e.g., De Young 1989; Rees 1989; Choskhi 1997; Gopal-Krishna & Wiita 2001; Gopal-Krishna, Wiita & Osterman 2003; Silk 2005; Barai & Wiita 2006, 2007) or inhibiting it in the case of a single-phase IGM (e.g., Rawlings & Jarvis 2004; Scannapieco, Silk & Bouwens 2005). The role of large radio lobes in spreading magnetic fields (Kronberg et al. 2001; Gopal-Krishna & Wiita 2001; Gopal-Krishna et al. 2003; Barai et al. 2004) and in distributing metals (Gopal-Krishna & Wiita 2003; Gopal-Krishna, Wiita & Barai 2004) through the IGM may also be very significant.

The Levine & Gnedin (2005, hereafter LG) model builds upon that of Scannapieco & Oh (2004, hereafter SO) and we shall employ results from each of these papers in the following. Assume that the AGN injects thermal wind with kinetic energy $E_w = L_w \tau_{\text{act}}$, where $L_w (\equiv \epsilon_w L_{\text{bol}})$ is the kinetic luminosity, τ_{act} is the time the AGN is active in this mode and L_{bol} , the bolometric luminosity, is a measure of the accretion power. Then, if δ_m is the mean relative overdensity in the environment in which the AGN is situated (assumed to be constant over the relevant volume) then the radius of the (spherical) bubble inflated, for a time $t > \tau_{\text{act}}$ will be (LG)

$$R_S = 1.7 \text{ Mpc } E_{w,60}^{1/5} (1 + \delta_m)^{-1/5} (1 + z)^{-3/5} t_9^{2/5}, \quad (1)$$

where $E_{w,60} = E_w / 10^{60} \text{ erg}$, z is the redshift and t_9 is the time since the active phase began, in units of Gyr. The bubble should grow according to Eq. (1) until it reaches pressure equilibrium with the ambient environment, at which point the size of the bubble would be (LG)

$$R_P = 3.24 \times 10^{-5} \text{ Mpc } \left(\frac{3E_{w,60}}{4\pi P} \right)^{1/3}, \quad (2)$$

where the external thermal pressure due to the IGM, $P = (1 + \delta_m) n_b k_B T$; here its mean baryon density, $n_b = 3.3 \times 10^{-7} (1 + z)^3 \text{ cm}^{-3}$, and the typical IGM temperature, which is taken to be constant with epoch, is $T \simeq 1.5 \times 10^4 \text{ K}$ (LG). We note that it might be more appropriate to allow for the average IGM temperature to increase as z decreases (Cen & Ostriker 1999), but including this effect does not make significant changes in our argument, whereas considering expansion into a much hotter and significantly denser ICM would do so, in that the radii out to which the bubbles would expand supersonically would be much smaller (e.g., Sternberg et al. 2007).

At times after the wind energy has been completely injected, the velocity of the bubble's expansion is given by (SO)

$$v_S = 1470 \text{ km s}^{-1} E_{w,60}^{1/2} R_{S,\text{Mpc}}^{-3/2} (1 + \delta_m)^{-1/2} (1 + z)^{-3/2}, \quad (3)$$

where $R_{S,\text{Mpc}}$ is R_S in units of Mpc. This result assumes that τ_{act} is short compared the cooling time for the hot gas in the bubble so that radiative losses can be ignored; in addition, PdV work and the work done against the galaxy's gravity can also be ignored (SO, LG). These are all plausible approximations (e.g., Furlanetto & Loeb 2001). The final approximation involved in these formulae is that the inertia of the displaced galactic ISM is less than that of the IGM, which will be reasonable once R_S exceeds about 10 kpc.

We find that the corresponding equation for earlier times, $t < \tau_{\text{act}}$, is

$$R_S = 1.17 (\epsilon_w L_{\text{bol}})^{1/5} \rho_{\text{IGM}}^{-1/5} t^{3/5}, \quad (4)$$

where $L_w = \epsilon_w L_{\text{bol}}$, with L_{bol} the bolometric luminosity, and $\rho_{\text{IGM}}(z) = (1 + z)^3 (1 + \delta_m) \rho_{\text{IGM}}(0)$. In Eq. (4) and in all other expressions where the unit of the result is not specified, we are employing cgs units. At these earlier times we obtain

$$v_S = 3060 \text{ km s}^{-1} \left(\frac{\epsilon_w L_{\text{bol}}}{3.17 \times 10^{44} \text{ erg s}^{-1}} \right)^{1/3} R_{S,\text{Mpc}}^{-2/3} (1 + \delta_m)^{-1/3} (1 + z)^{-1}. \quad (5)$$

Note that one may reasonably expect that $L_w \leq L_B \sim 0.1 L_{\text{bol}}$, with L_B the B-band luminosity (LG; cf. Rawlings 2003). Therefore, values of ϵ_w between 0.01 and 0.1 are reasonable, with SO arguing for $\epsilon_w \approx 0.05$, and most of our computations assume such a value. However, other authors have argued that the power in the mechanical outflow can substantially exceed L_{bol} (Churazov et al. 2002, 2005; Peterson & Fabian 2006); this situation may be generally the case for radiatively inefficient accretion onto black holes (e.g., Hopkins, Narayan & Hernquist 2006).

The outflowing wind carries enough momentum to carve out a low density cavity or bubble, but it is also depositing some mass into that bubble. To provide an estimate of the

density of this bubble through which the jets later will be propagating in our scenario, we must introduce another parameter, which can be taken to be the wind speed, v_w . Then we have an expression for the rate at which mass is ejected in the non-relativistic wind \dot{M}_w

$$\dot{M}_w = 2L_w v_w^{-2} = 6.3 \times 10^{27} \text{ g s}^{-1} v_{w,4}^{-2} E_{w,60} \tau_8^{-1}, \quad (6)$$

with $v_{w,4} = v_w / (10^4 \text{ km s}^{-1})$ and $\tau_8 = \tau_{\text{act}} / 10^8 \text{ yr}$. A plausible, but by no means rigid, constraint on the rate at which mass outflows in this wind is that it should be less than the mass accretion rate needed to power the AGN. Using the typical parametrization for an standard (radiatively efficient) accretion disk, where $L_{\text{bol}} = \epsilon_{\text{acc}} \dot{M}_{\text{acc}} c^2$, where $\epsilon_{\text{acc}} \sim 0.1$, we find that if we adopt the above constraint

$$v_w > (2\epsilon_k \epsilon_{\text{acc}})^{1/2} c = 0.045c \epsilon_{k,-2}^{1/2} \epsilon_{\text{acc},-1}^{1/2}. \quad (7)$$

Thus the minimum wind speed for a radiatively efficient accretion flow is, $v_{w,\text{min}} \simeq 10^4 \text{ km s}^{-1}$, where we have evaluated Eq. (7) taking $\epsilon_k = 0.01$ and $\epsilon_{\text{acc}} = 0.057$, the latter being the minimum value for thin disk accretion onto a non-rotating black hole (e.g. Shakura & Sunyaev 1973). It is, however, important to note that substantially lower wind speeds are allowed if the accretion rate is sufficiently low so that a radiatively inefficient accretion flow (e.g., Narayan & Yi 1994) is established. It is under these circumstances that L_w can exceed L_{bol} .

Since the total mass ejected in the wind up to time $t < \tau_{\text{act}}$ is $\dot{M}_w t$, the mean density in a wind-filled bubble is

$$\begin{aligned} \rho_b(t) &= 3\dot{M}_w t / 4\pi R_S^3(t) \\ &= 0.298 (L_{\text{bol}} \epsilon_w)^{2/5} t^{-4/5} \rho_{\text{IGM}}^{3/5} (0)(1+z)^{9/5} (1+\delta_m)^{3/5} v_w^{-2}, \end{aligned} \quad (8)$$

where we have used Eq. (4).

However, once $t > \tau_{\text{act}}$, R_S is better approximated by Eq. (1) and no more mass is injected, giving $M_w = \dot{M}_w \tau_{\text{act}} = 2E_w / v_w^2$ and thus

$$\begin{aligned} \rho_b(t) &= 3M_w / 4\pi R_S^3(t) \\ &= 0.298 E_w^{2/5} t^{-6/5} \rho_{\text{IGM}}^{3/5} (0)(1+z)^{9/5} (1+\delta_m)^{3/5} v_w^{-2}. \end{aligned} \quad (9)$$

So the bubble density declines faster after a time τ_{act} ($\propto t^{-6/5}$) than it did before that time ($\propto t^{-4/5}$) even though the radius expands more slowly for $t > \tau_{\text{act}}$. This gas density is usually extremely low, but the temperature of this gas is typically hot enough to produce some X-ray emission (e.g., Krause 2005).

3.2 Jets Launched into the Bubble

We now assume that at time t_j , measured from the onset of the wind outflow, a pair of jets of equal kinetic power is launched; the total power in the jets is L_j . We will further assume that L_j remains constant throughout the duration of the jets' ejection, τ_j . Because the jets are both focussed and ploughing through a low density medium in the wind-swept bubble, they will propagate outward substantially faster than would a quasi-spherical wind of similar power. Two-dimensional hydrodynamic simulations of a particular case of a pair of very powerful jets propagating through a supersonic bubble produced by a supernova driven galactic wind have recently been performed by Krause (2005). These computations were designed to explain the clumpy

HI absorption seen in many high- z RGs in terms of instabilities produced in the wind shell upon penetration by the jet. They clearly show that a powerful jet launched a long time ($t_j = 80 \text{ Myr}$ in this case) after the wind initiation will, as we assume, produce a narrow cocoon within the bubble. Then, after passing through the bubble wall, the jet will continue to propagate more slowly in a denser ambient medium, but will still produce extended overpressured lobes (Krause 2005). These simulations neglected magnetic field in the bubble, whereas we expect the bubble to become magnetized, even if it was not originally so, due to some mixing with the synchrotron plasma of the radio lobes blown by the jets during their passage through the bubble. Any magnetization should enhance the bubble's stability against surface distortions (e.g., Kaiser et al. 2005; Lyutikov 2006).

Following the basic arguments of Kaiser & Alexander (1997) and calibrating the models through catalogs of powerful radio galaxies (Blundell, Rawlings & Willott 1999; Barai & Wiita 2006, 2007) we have a lower bound on the distance out to which a jet of average collimation will have propagated within the bubble, at time $t > t_j$,

$$R_j(t) \geq 1.57(t - t_j)^{3/5} L_j^{1/5} \rho_b^{-1/5}(t_j), \quad (10)$$

as long as we ignore the spatial gradient in density within the bubble, which is an approximation adequate for our purposes. The above expression could be an equality if ρ_b did not continue to decline after t_j ; however, if the velocity at which the jet moves is sufficiently high compared to the rate of expansion of the bubble after the launch of the jet (as usually will be the case in the situations of interest to us), then this continuing temporal decline of ρ_b has only a small effect, which we shall ignore. Hence the numerical results are computed assuming Eq. (10) is an equality. Only if $t_j \ll \tau_{\text{act}}$ and M_w is large do we have such high values of $\rho_b(t_j)$ that the jets will have inordinate difficulty in catching up to the wind under the approximation we employ; under these circumstances the continued decline in ρ_b with time really should be considered. In the following exploratory calculation we also ignore the slowing down the jet would suffer while penetrating the reverse shock and the denser shell of material swept up by the expanding bubble. In addition, we ignore the modest acceleration produced in the boundary of the bubble through the extra pressure injected by the jet. We note that this slowing of the jet's relative speed with respect to that of the wind arising from these effects is roughly offset by the relative acceleration produced by the continuing temporal decline of the bubble density.

In Fig. 1 we display the expansion of both the wind-blown bubble and the jets launched later for four representative combinations of parameters. The decline of the bubble expansion rate is seen at 100 Myr. In one illustrated case the jet never catches up to the wind's boundary since this jet is launched 50 Myr after the wind and is, moreover, energised for only 10 Myr. In the other three cases, the jets do catch up to the bubble boundary, despite having a shorter lifetime (in one case) and lower total energies (in two cases). Once the jets pass through the bubble and enter the IGM their velocities of advance are seen to change. With our assumptions that the bubble continues to inflate even after the AGN wind is shut off, while the jet-fed cocoons stop growing right after the jet is switched off, we see that in all three of these displayed cases the bubble boundary could eventually

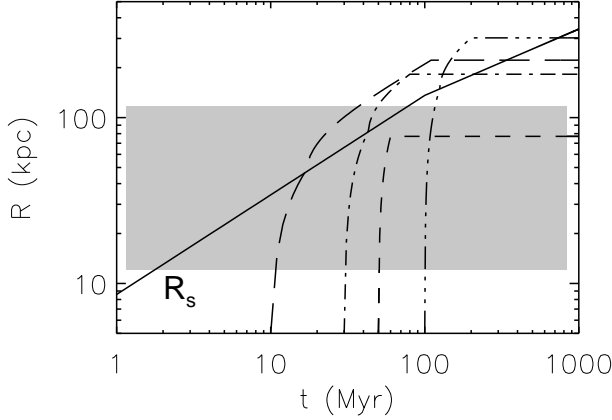


Figure 1. Radii of a wind-blown bubble, R_S , and of four jets launched within that bubble. The solid curve shows R_S for the following parameters: $L_w = 5 \times 10^{42} \text{ erg s}^{-1}$, $\tau_{\text{act}} = 100 \text{ Myr}$, $z = 1.0$, $\delta_m = 5.0$, $v_w = 3000 \text{ km s}^{-1}$. The other curves are propagation distances for the jets, all of which have $L_j = 5 \times 10^{42} \text{ erg s}^{-1}$. Jet parameters are: $t_j = 10 \text{ Myr}$ and $\tau_j = 100 \text{ Myr}$ (long-dashed); $t_j = 30 \text{ Myr}$ and $\tau_j = 50 \text{ Myr}$ (dot-dashed); $t_j = 50 \text{ Myr}$ and $\tau_j = 10 \text{ Myr}$ (short-dashed); $t_j = 100 \text{ Myr}$ and $\tau_j = 100 \text{ Myr}$ (triple-dot-dashed). The grey band shows the plausible values of R_{eq} , with lobe magnetic fields of $3.0 \times 10^{-5} \text{ gauss}$ and $1.0 \times 10^{-6} \text{ gauss}$ corresponding to its lower and upper boundaries, respectively.

once again overtake the jet; however, thanks to the confinement exerted by the cocoon on the bubble in the interim, the times when this occurs that can be read from Fig. 1 are underestimates.

We can now define the catch-up time, t_c , and catch-up radius, R_c , through the relation $R_j(t_c) = R_S(t_c) \equiv R_c$. The formula in Eq. (10) is valid for $t_j < t < t_c$, but at later times the jets are ploughing through the constant density IGM, and we have for $t_c < t < t_j + \tau_j$

$$R_j(t) = R_c + 1.57(t - t_c)^{3/5} L_j^{1/5} \rho_{\text{IGM}}^{-1/5}(z). \quad (11)$$

In Fig. 2 values for R_c are plotted against t_j , the time interval between the wind's onset and the jets' launching, for substantial ranges of the most important input parameters. Each of the panels shows the results for two or three different jet powers. The values of R_P (imposed by the IGM; Eq. 2) are shown in Figs. 2a and 2b for $E_w = 1.58 \times 10^{57} \text{ erg}$ and $E_w = 1.58 \times 10^{58} \text{ erg}$, respectively, while the corresponding values of R_P for $E_w = 3.16 \times 10^{58} \text{ erg}$ (Fig. 2c) and $E_w = 3.16 \times 10^{60} \text{ erg}$ (Fig. 2d) exceed 2 Mpc and are not shown. The convention used in Fig. 2 is that if the jet never catches up to the bubble's boundary then R_c is plotted as R_P .

Under most circumstances we see that R_c rises as t_j increases, as expected, since a jet should take longer to catch up to a bubble which has had a greater head-start. In all cases, more powerful jets obviously produce lower values of R_c for fixed values of t_j . The less powerful jets (e.g., $L_j/L_w = 0.2$ in Figs. 2a, 2b and 2d; $L_j/L_w = 1.0$ in Figs. 2b and 2d), and even very powerful, but short-lived, jets ($L_j/L_w = 3.0$ in Fig. 2d) may never catch up to the wind boundary if the jet's launch is sufficiently delayed. The assumption that ρ_b is fixed at the value it has attained at t_j

Figure 3. An illustration of three stages in the production of superdisk through the initial inflation of a wind-blown bubble to the recompression of the bubble by the radio lobes after the jets have penetrated through it. [Submitted as a .jpg file.]

leads to the peculiar results plotted at low values of t_j in Figs. 2a, 2b, and 2d for some of the adopted values of jet power. Because these nominal densities can be quite high for small values of t_j (see Eq. 8) the jets appear to never catch up to the wind boundary; since, in actuality the bubble density would continue to decline, unless the jets were very short-lived they would indeed eventually catch up to the wind's boundary.

We shall now briefly examine some broad implications of the above analytical scheme, taking a fiducial values of $E_w \sim 10^{59} \text{ erg}$ for the kinetic energy of the wind outflow and the same value for the kinetic energies of the relativistic jets. From Eq. (1) and Fig. 2, it is seen that if the bubble's expansion is allowed to continue much after cessation of the wind outflow ($\tau_{\text{act}} \approx 10^8 \text{ yr}$), then in the course of $\sim 10^9$ years it would have grown to a quasi-spherical volume of size around 1 Mpc if it encounters an ambient IGM pressure $< 10^{-16} \text{ dyne cm}^{-2}$; this will be the case provided the AGN is located the field, rather than inside a dense cluster environment, and is not at too high a redshift so that the combination $\delta_m(1+z)^3 < 150$.

However, if a relativistic jet is subsequently launched, then once it crosses the bubble's boundary, the much higher pressure of its radio lobe would begin to act as a wall, blocking, and even reversing the bubble's expansion along the jet's direction. The cartoon in Fig. 3 shows this as the last phase of this dual mode AGN energy output.

The pressure in the radio lobe is indeed much higher than the IGM pressure, since it is given by $P_{\text{lobe}} \simeq 8 \times 10^{-14} B_{-6}^2 \text{ dyne cm}^{-2}$, assuming the minimum energy condition which signifies an energy equipartition between magnetic and relativistic particles; here B_{-6} is the lobe field in microgauss and values of B_{-6} between 1 and 30 are typically estimated for FR II RGs. Inserting this value of P_{lobe} into Eq. (2) yields an equilibrium radius of the bubble, $R_{eq} \simeq 0.22 \text{ Mpc } E_{w,59}^{1/3} B_{-6}^{-2/3}$, which is in the range from a few to hundreds of kiloparsecs. These values are also displayed in Figs. 1 and 2 as grey bands corresponding to the range of values of B mentioned above.

Note that the higher pressure in the radio lobes may even reverse the expansion of the bubble boundary in the areas of contact with the lobes if $R_c > R_{eq}$. Thus, the actual width of the gap between the radio lobes should be between $2R_{eq}$ and $2R_c$, assuming that the jets live long enough and are launched soon enough to overtake the bubble. The consistency of these estimates with the observed widths of the radio gaps in SDs argues for the efficacy of the wind's confinement by the lobes, as envisioned in our model. We can estimate the time scale over which this recompression along the jet axis from R_c to R_{eq} could occur as

$$\Delta t \simeq 2.5 \times 10^7 \text{ yr} \left(\frac{R_c}{100 \text{ kpc}} \right)^{1/2} \left(\frac{R_c - R_{eq}}{100 \text{ kpc}} \right)^{1/2} \times (1+z)^{3/2} (1+\delta_m)^{1/2} B_{-6}^{-1}. \quad (12)$$

As long as $\tau_j > t_c + \Delta t$ this recompression is expected to be

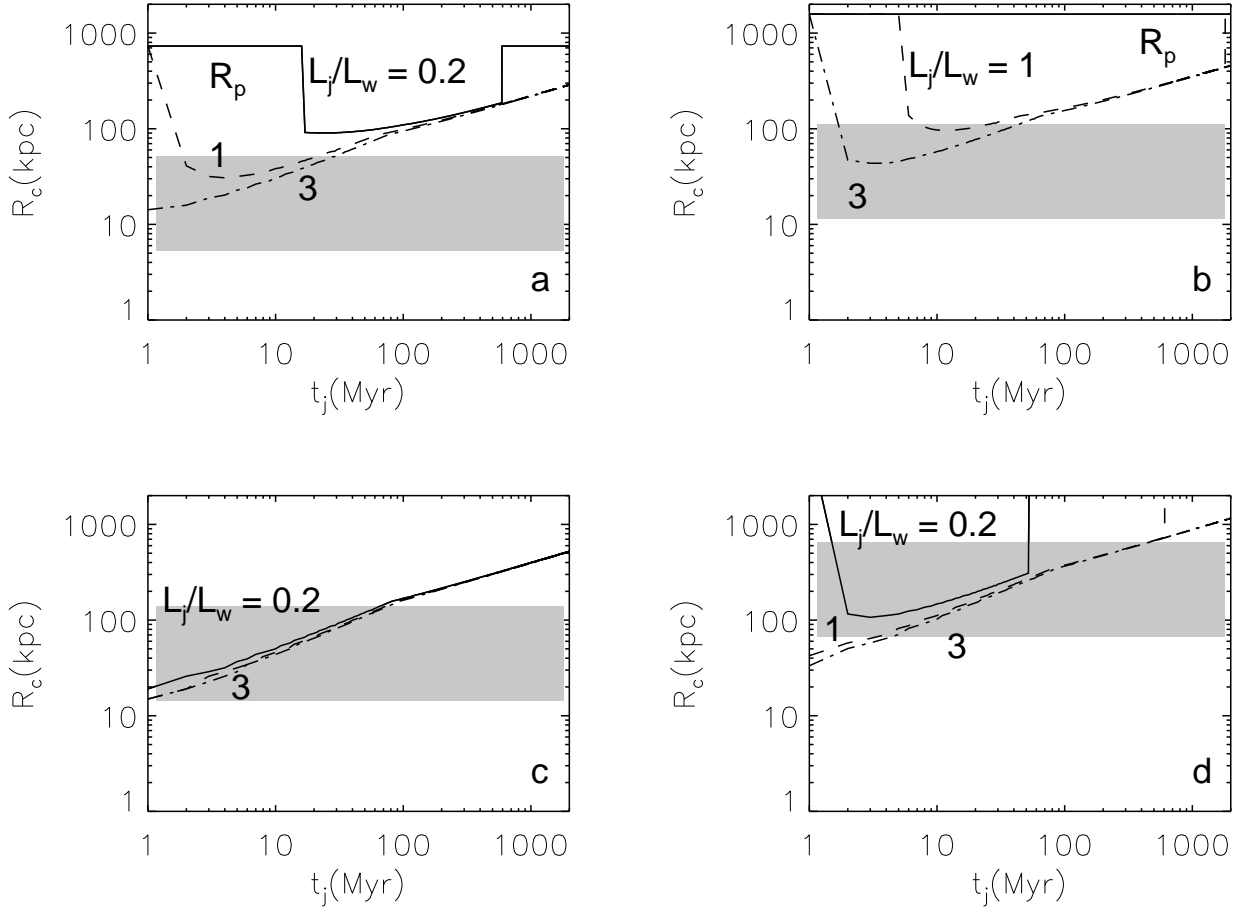


Figure 2. Catch-up radii, R_c , as functions of t_j , shown for three different ratios of the jet to wind luminosities: 0.2 (solid), 1.0 (dashed), 3.0 (dot-dashed). All panels share the following parameters, $z = 1$ and $\tau_{\text{act}} = 1.0 \times 10^8 \text{ yr}$, and a)-c) also share the following parameters, $\delta_m = 5$, $\epsilon_w = 0.05$, and $\tau_j = 1.0 \times 10^8 \text{ yr}$. The other parameters are: a) $L_w = 5.0 \times 10^{41} \text{ erg s}^{-1}$, $v_w = 1.0 \times 10^3 \text{ km s}^{-1}$; b) $L_w = 5.0 \times 10^{42} \text{ erg s}^{-1}$, $v_w = 1.0 \times 10^3 \text{ km s}^{-1}$; c) $L_w = 1.0 \times 10^{43} \text{ erg s}^{-1}$, $v_w = 1.0 \times 10^4 \text{ km s}^{-1}$; d) $L_w = 1.0 \times 10^{45} \text{ erg s}^{-1}$, $v_w = 1.0 \times 10^4 \text{ km s}^{-1}$, and now $\delta_m = 10$, $\epsilon_w = 0.10$ and $\tau_j = 3.0 \times 10^7 \text{ yr}$. As in Fig. 1, the shaded areas delineate values of R_{eq} for lobe magnetic fields between $30 \mu\text{G}$ (lower boundary) and $1 \mu\text{G}$ (upper boundary); R_P is shown in a) and b).

important and the half-width of the superdisk is likely to be close to R_{eq} . It should be noted that the compression would probably be enhanced by a dynamic pressure arising from the back-flow in the radio lobes, which has been found to be present in simulations of radio jets (e.g., Hooda & Wiita 1998). Nonetheless, R_c provides an upper limit to this half-thickness under most circumstances where both winds and jets are important carriers of AGN output.

If the value of t_j is so small and the jet luminosity is so large that $R_c < R_{eq}$, then the pressure inside the bubble may still be greater than that inside the lobes for some values of $t > t_c$. In this case the bubble may continue to expand in all directions until $R_S \simeq R_{eq}$, though a somewhat smaller maximum value along the jet directions is expected because of the additional ram pressure exerted by the backflow in the lobe. So again, the width of any observed superdisk should be between $2R_{eq}$ and $2R_c$.

Beyond this stage, the subsequent expansion of the bubble's plasma would be confined to a plane roughly orthogonal to the jets' direction, giving rise to a pancake-like region

filled with the hot outflowing wind material. Of course, as mentioned above, in the extreme cases where the bubble's confinement by the overtaking lobes begins to take place after a very long time ($t_c \sim 10^9 \text{ yr}$), which is conceivable for giant radio galaxies, the radio gap could approach megaparsec dimensions, as seen for the radio galaxy 0114–476 (Saripalli et al. 2002).

4 DISCUSSION AND CONCLUSIONS

If AGN activity usually involves both quasi-spherical wind outflows and the subsequent launching of collimated jets the latter will frequently overtake the former and can produce large gaps between the radio lobe pair, particularly in the higher redshift RGs which are yet to acquire a substantial, high-pressure circumgalactic medium. Here we have employed a highly simplified model to estimate some of the key properties of these wind/jet interactions.

It is important to recall that we have made several

assumptions and approximations, most of which were discussed in Sect. 3: (i) spherical symmetry of the wind; (ii) neglect of the mass of the host galaxy’s ISM which is mostly swept into a shell; (iii) neglect of the reverse shock behind the wind; (iv) neglect of work done against the galactic gravitational potential and of PdV work done by the expanding bubble; (v) neglect of the likely correlated growth in overdensity and temperature in the filamentary IGM; (vi) neglect of the decline with time of ρ_b for $t_j < t < t_c$; (vii) neglect of the additional pressure inside the lobes for $t_j < t < t_c$; (viii) ignoring the possibility that for $t_c < t < \tau_{\text{act}}$ the continuing outward wind flow could destabilize the jet (Norman, Burns & Sulkanen 1988); (ix) assuming that the bubble continues to grow after τ_{act} , while cutting the growth of the jets immediately after $t_j + \tau_j$. Removing approximations (iii) and (vii) would tend to increase R_c and t_c ; however, eliminating approximations (iv), (v) and (vi) would decrease those quantities, and hence typically narrow the observed superdisks. Approximation (ii) reduces $R_S(t)$ but it also reduces $R_j(t)$ and so its effect on R_c is unclear. The early destabilization of a not very supersonic jet by a very supersonic wind (removing approximation viii) would not change R_c , but would reduce the chance of bubble compression. Allowing for the relaxation of assumption (ix) can lower R_c and has the opposite effect on continuing compression. Clearly, a more appropriate way to treat this problem would be through detailed hydrodynamical simulations which would allow the relaxation of all of the above assumptions, but given the countervailing tendencies noted above, we feel confident that our basic results are quite plausible, although no numbers we provide can be considered precise. We have already emphasized that the IGM conditions we consider are appropriate for powerful (FR II) RGs forming during the peak of the radio luminosity function at $1 < z < 3$ (e.g., Grimes, Rawlings & Willott 2004). In GKW00 we provided indirect evidence for superdisks in Ly α galaxies in and above this redshift range; however, our explicitly mapped examples of RGs with superdisks must be drawn mostly from closer objects for which radio maps with adequate resolution and dynamic range are available, and for which the actual conditions are often more similar to those of the ICM at lower redshifts. Under those circumstances the typical sizes for wind inflated bubbles would be compressed to a few kpc.

We now summarize some salient features of our model.

(1) Superdisks (at least the wider ones) mark *giant* planar conduits along which the AGN’s non-relativistic wind is able to escape preferentially, i.e., in directions roughly perpendicular to the radio axis along which synchrotron plasma is transported. We suggest that the surface of dynamical interaction between the wind bubble and the radio lobe pair can often give rise to well-defined, planar boundaries between the two media, which we identify as *lobe-wind interfaces* and which may be manifested in the RGs as central emission gaps or superdisks. (In most RGs, however, the viewing angle would work against the sharp edges, i.e., a superdisk morphology, being observed). The metal enriched gas swept out of the host galaxy is thus transported to great distances, not only by being dragged along by the jets, but in the perpendicular direction as well (through the superdisk). Thus, the AGN activity would tend to isotropize the metal enrichment process, as is indeed found from measurements (de Grandi et al. 2004).

(2) This scenario provokes us to revisit the question raised three decades ago by Jenkins & Scheuer (1976): “what docks the tails of radio source components?” They concluded that the cause is other than synchrotron losses. Later, an explanation was proposed in terms of blocking of the radio lobe plasma by the ISM of the host galaxy (e.g., Leahy & Williams 1984). In our picture, on the other hand, the sharp and straight edges of the strip-like central gaps in the radio bridge signify *active surfaces* where the thermal wind outflowing from the AGN is actually countered and redirected by the lobe overpressure assisted by the dynamic pressure of the back-flowing relativistic plasma inside the radio lobes. Eventually, when the pressure of this back-flow has declined sufficiently, it could even mix with and be dragged along the thermal wind escaping in the perpendicular direction.

(3) If indeed the “wind” outflow precedes the radio jet ejection, the pancake or superdisk resulting from the lobe-wind interaction can become “frozen” in space quite early in the active phase of the galaxy. Now, if the galaxy has a large enough component of motion normal to the superdisk (say, 500 km s^{-1} or more), it may even move out of the latter into the lobe during its active lifetime. Two RGs exemplifying such a situation are 3C 16 and 3C 19, where the host galaxy is seen *outside* the radio gap (Harvanek & Hardcastle 1998; Leahy & Perley 1991; Gilbert et al. 2004). While such a morphology is expected only in extreme cases, it is quite conceivable in our picture but hard to understand within the usual interpretation of the radio gaps invoking a buoyancy led outward squeezing of the radio lobes by the denser ISM of the parent galaxy.

(4) Notwithstanding the sharp, quasi-planar boundaries of the radio gap, the present model does allow for some fainter radio emission seen within the gap (being remnant of the early phase when the radio jets were still boring their way through the bubble). Examples of this can be found in the radio sources J1137+613 (Lara et al. 2001) and J1628+3932 (de Breuck et al. 2004). Other possible manifestations of this situation are 3C 63 (Harvanek & Hardcastle 1998), 3C 136.1 (Leahy & Williams 1984), and 3C 300 (Leahy & Williams 1984; Hardcastle et al. 1997). However, such remnant emission usually will be difficult to see without high dynamic range observations and will not last very long compared to the total lifetime of the radio source. This is because this inner radio emitting plasma will be cut off from a continued supply of the backflow from the lobes and will be mixed up and dispersed with the thermal outflow through the chimney (i.e., superdisk).

Finally, although the scenario sketched here has been quantified in a highly simplified analytical form, the possibility of the sharp-edged radio gaps being wind-lobe interfaces, i.e., “active” surfaces of dynamical interaction between the thermal and nonthermal outflows, may have other interesting observational and theoretical consequences. Hence, this general picture needs to be explored further. Full hydrodynamic simulations of this situation are worth pursuing. On the observational side, detailed radio imaging of high- z radio galaxies would provide useful input and constraints on the basic model presented here.

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